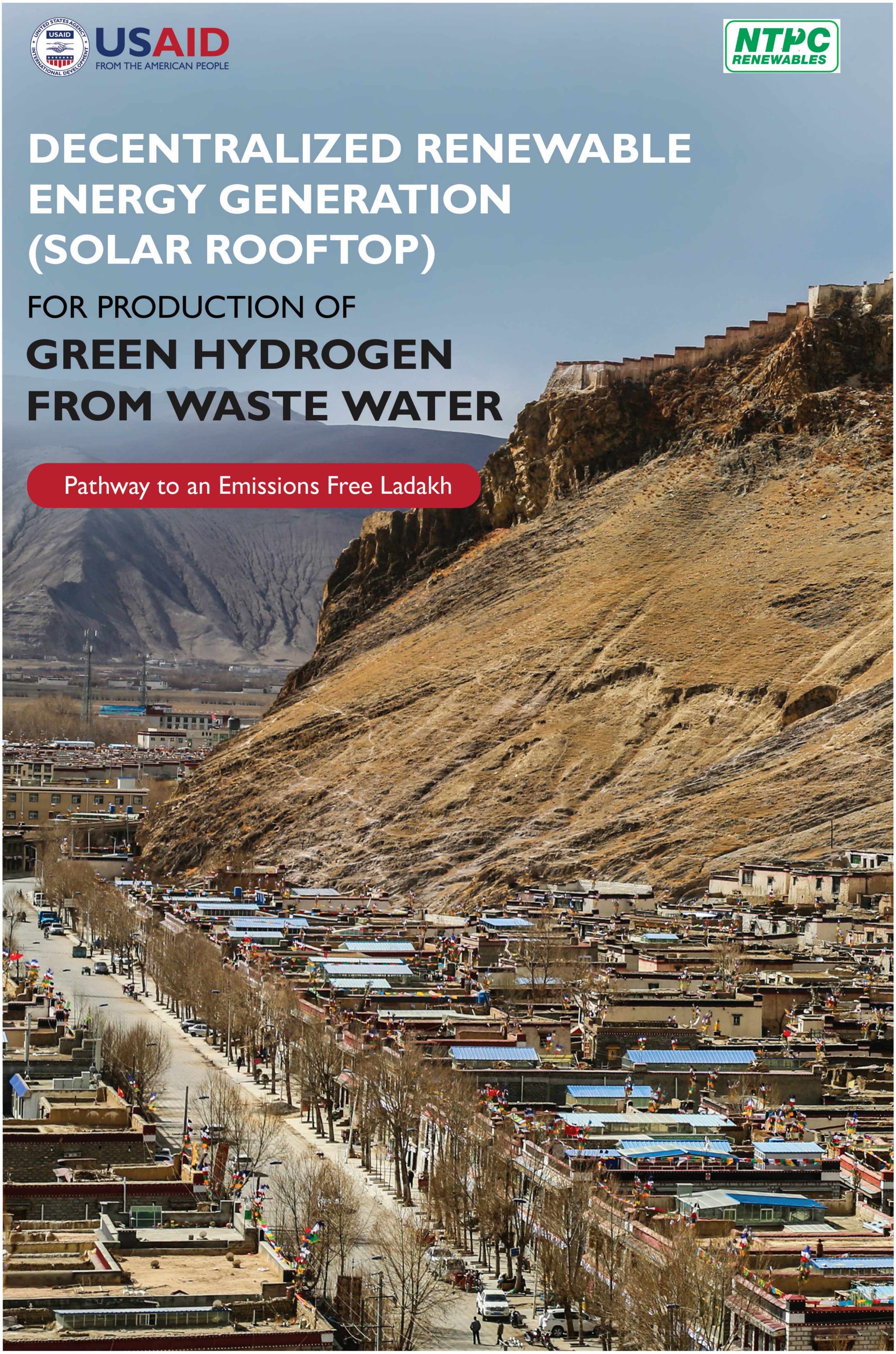

DECENTRALIZED RENEWABLE ENERGY GENERATION (SOLAR ROOFTOP)

FOR PRODUCTION OF

GREEN HYDROGEN FROM WASTE WATER

Pathway to an Emissions Free Ladakh

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Contents

Executive summary

Green hydrogen offers an immense potential as a clean fuel and a feedstock for use in industrial applications and as a fuel for transportation and power generation. Globally, there is an immense optimism and many nations have developed policies and roadmaps for the gradual incorporation of hydrogen in various industries which are conventionally reliant on fossil fuels.

The production of green hydrogen via electricity sourced from renewable power leads to zero emissions during its generation and utilization. Green hydrogen has the potential to reduce and gradually eliminate the heavy dependency of Leh on diesel and create a pathway for achieving its Net Zero ambitions.

The geographical region in which Leh is located has a combination of extremely high solar irradiance all throughout the year and low ambient temperatures. Both these factors contribute towards a high energy production from solar panels. In this project, the electricity generated from solar panels is intended to be used for the generation of green hydrogen using electrolyzers. The proposed approach consists of installation of distributed solar installations across numerous buildings including homes, commercial places and government buildings. The collective electricity generated will be directed through the existing electric grid and will be drawn by the electrolyzer at the city substation. The solar subsidy offered by the central government and the government of Leh for installation of solar rooftops further assists in achieving lower levelized cost of hydrogen (LCOH). Keeping in mind the water scarcity in the region, the project proposes the usage of water from the sewage treatment plant (STP) as feedstock for the electrolyzer.

The electrolyzers, hydrogen storage and the hydrogen refuelling station will be installed close to an identified substation, which is located next to a prominent highway. The sewage treatment plant (STP) will require minor upgradation in the form of setting up a tertiary treatment unit which will facilitate another level of water purification on-site. The purified water will be transported to the electrolyzer , a distance of 8-10 kms.

The generated hydrogen is proposed to be used as fuel for two applications namely; heavy vehicles (buses and trucks) and for stationary power generators (replacement for diesel generators). This project demonstrates the effectiveness of green hydrogen in reducing the usage of diesel in two sectors which are currently heavily reliant on the diesel. The Indian Army stationed in Leh has a large fleet of buses and trucks for their internal usage and they are keen to adopt hydrogen powered vehicles into their fleet for demonstration and evaluation purposes. Diesel generators are heavily used by the army as well as by the tourism industry in hotels and restaurants which offer abatement potential.

Key highlights of the proposed project are as follows:

- Total solar capacity of **7.2 MW** will be set up and will consist of **2400** individual installations of **3 kW** capacity

- The average daily generation of electricity will be **35.6 MWh**. Out of this **20 MWh** will be used daily by the electrolyzer for the generation of hydrogen.

- The remaining electricity will be sold to the grid at the Average Power Purchase Cost (APPC). For the purpose of calculations, this is assumed to be **4.5 INR/kWh.**

- A monthly rent is proposed to be paid to the building owner for allowing the installation of the solar panels on their rooftop by the developer company.

- Considering all the above factors, the calculated electricity tariff is **1.34 INR/unit** and this is taken as the input cost for the calculation of LCOH

- The proposed electrolyzer size is **2 MW** and is expected to operate at the rated power for 10 hours per day. The daily average hydrogen generation will be approximately **330 kg**.

- The levelized cost of hydrogen (LCOH) is estimated to be **371 INR/kg** at the electrolyzer output and **578 INR/kg** after considering the storage and dispensing costs.

- The generated hydrogen will be used to fuel **6** heavy vehicles and **600 kW** of fuel cell based electricity generators.

- The total annual diesel savings enabled by the hydrogen is estimated at **5** lakh litres per year.

- The total annual emissions savings due to diesel replacement are estimated at **1322** tons of **CO_2**, **2389 kg** of **NOx**, **1195 kg** of **SOx** and **1.0 kg** of particulate carbon.

- The project has good replicability potential, not only in other parts of Ladakh but also in several other cities in India.

- Reducing the dependence on diesel and replacing it with a locally produced clean fuel such as hydrogen is in line with the objectives of Atmanirbhar Bharat and the Net Zero Targets.

01. Introduction

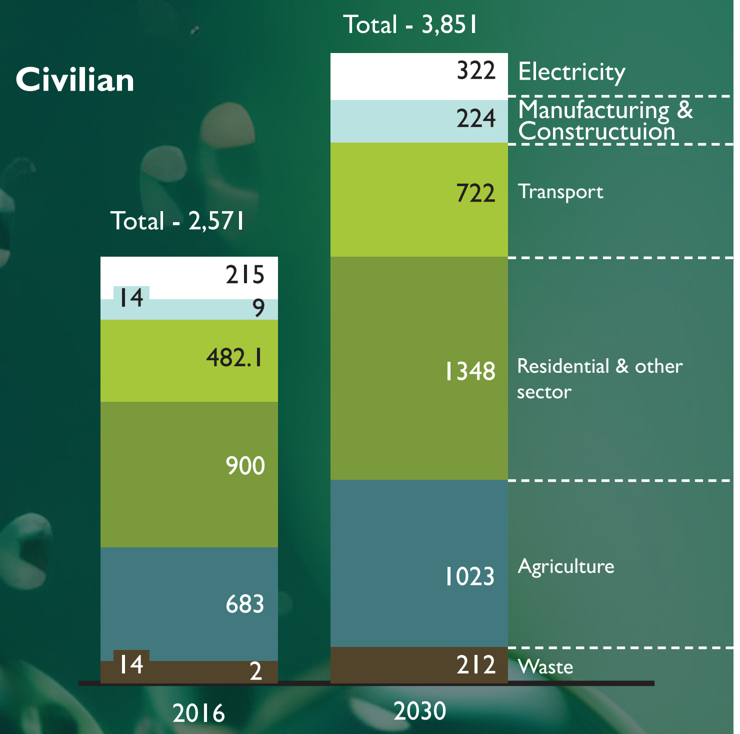
Green hydrogen as a fuel has garnered global attention due to its many benefits and owing to its wide impact on a variety of industries, transportation and power generation. It has the potential to decarbonize hard-to-abate sectors and facilitate countries towards achieving their net zero targets. Several countries have laid out their hydrogen roadmap and many projects are being set up worldwide for the generation and utilization of green hydrogen in a variety of industries.

The major cost input for the production of green hydrogen is the cost of the renewable electricity which is used to power the electrolyzers. As a nation, India is blessed with abundant solar potential throughout most parts of the country and this is immensely beneficial for attaining a low cost of hydrogen production. By capitalizing on this, India can expect to lower its dependence on imported fossil fuels and also strive towards becoming a net exporter of energy in the form of green hydrogen.

Leh is heavily dependent on diesel for a large part of its energy needs. This diesel has to be transported to the region from far off locations by road. It results in high transportation costs and faces logistical challenges from road closure specially during the harsh winter season. Leh is in need of a clean fuel which can fulfill its aspirations for economic growth and do so in a manner which preserves the fragile ecosystem and the natural beauty of the region. One additional challenge in Leh is that the dwellings and habitations are sparse and far apart making the setting up of dedicated transmission lines expensive. The approach described in this project enables local generation and local usage of a green fuel which can be scaled up in parallel to the economic growth of the region.

The presented analysis in this report is divided into 10 chapters. In chapter 2, the identified use cases for green hydrogen are discussed along with their expected impact on emissions reduction, total cost of ownership of the proposed hydrogen-based vehicles and unit cost of electricity produced from fuel cell based power generation. In chapter 3, the approach and work methodology employed to conduct the presented analysis is described. In chapter 4, the procedure for estimation of the solar rooftop area using image processing from maps is described. The total solar irradiance data for Leh is used to estimate the daily, monthly and annual solar generation potential. These two analyses are combined to arrive at the total solar power generation potential of Leh.

Figure 1: GHG inventory in ladakh (in KTPA CO2e)



Source: Government of Ladakh document

Defence
GHG emission in 2022 is - 15,00 kTPA CO2e

In chapter 5, key aspects of the electrolyzer sizing and technology selection are analyzed and the hydrogen storage requirement is also estimated. Chapter 6 focuses on the issues relating to the water requirement, water quality and the required technology for converting the sewage treatment plant (STP) water into suitable quality of water to be used as feedstock in the electrolyzer. In chapter 7, details regarding the selection of the site for setting up of the green hydrogen plant are presented. In addition to this, the analyzed results of a survey of the local population to gauge their willingness for allowing solar installations on their rooftops is presented.

Chapter 8 focuses on the financial analysis of the entire project, which includes the estimated cost of green hydrogen (GH2) production, total project cost and the calculated Viability Gap Funding (VGF) requirement. Further to this, in chapter 9, the replicability potential of this project to other cities in India is explored and a risk analysis of the current project is presented. Chapter 10 summarizes all the key recommendations for this project and the way forward for its successful execution.

02. Use cases and cost benefits analysis

The green hydrogen produced daily by our proposed system has two primary applications: transportation vehicles and stationary power. The transportation vehicles will consist of heavy vehicles (buses and trucks), whereas the stationary power generation systems will consist of fuel cell units rated between 5 – 50 kVA.

In transportation, heavy vehicles (buses and trucks) are recommended for deployment for army application. Two buses and three trucks running 300-500 km per day can be comfortably operated by the available hydrogen. A few smaller vehicles such as SUVs, 3-wheeler, 4-wheeler cargo vehicles and golf-carts can also be considered for deployment.

Transportation

Figure 2: Hydrogen for transportation

3 Buses

34 Kg H2/ Day / Bus
Total = 102 Kg

3 Trucks

34 Kg H2/ Day / FCEV truck
Total = 102 Kg

Total Daily Green Hydrogen Requirement of ≈ 200 Kg

The calculated per unit cost of electricity generated from a hydrogen-based fuel cell generator is currently higher than that of a similarly sized Diesel generator. The difference is reduced significantly if we consider the additional benefits of residual heat from the fuel cell which can be used for space heating.

Our system is designed to generate an estimated 330 kg of hydrogen each day. Out of this, 200kg will be utilized for transportation purposes and the remaining 130 kg for stationary power generation. Both transportation and stationary generation applications are technically suitable for deployment in Leh.

Stationary power (CHP)

Figure 3: Hydrogen for stationary power generation and space heating

System sizes (kVA)	Daily power generation (kWh)	Daily hydrogen consumption (Kg)	No. of systems	Daily consumption (Kg)
5	12	1.1	30	32
10	24	2.2	10	22
20	48	4.4	10	44
50	120	10.9	3	33

Total daily green hydrogen requirement of 130 Kg

2a. Transportation

In the current project, five hydrogen fuel cell electric vehicles (H2-FCEV) are proposed to be acquired and operated. These five vehicles would include three buses and three trucks and will be equipped each with a hydrogen storage capacity of 34 kg and an achievable mileage of approximately 12 km/kg of Hydrogen. Under loaded conditions, these vehicles enable a driving range of 400 km on a single refueling of the hydrogen. The total daily hydrogen requirement of these vehicles collectively would be 200 kg.

Our analysis shows that the transportation sector will be the major consumer of the hydrogen produced. Considering the levelized cost of hydrogen (LCOH) calculated previously, the total cost of ownership (TCO) per kilometer for these vehicles has been determined to be 104/km.

Green hydrogen bus running cost (INR)

104/Km

Hydrogen refueling infrastructure for mobility

The generated green hydrogen will be stored locally in the dedicated hydrogen storage facility to be set up on-site and in close proximity to the electrolyzer. The facility will have a storage capacity of 330 kg of hydrogen which is equivalent to the average daily production from which 200 kg of hydrogen is utilized for transportation.

The stored hydrogen can be directly supplied to the hydrogen fuel cell vehicles (H2-FCEV) through the dispensing station which will also be located close to the electrolyzer. The fuel cell vehicles are normally expected to be refueled once per day depending on the usage of the vehicle. The distance driven per day and the payload may vary significantly and, in some cases, a second refueling may be required. The time required for refueling each vehicle starting from an empty tank would be between 8-10 minutes.

Faster refuelling

10 minutes

2b. Stationary power generation using hydrogen fuel cell

Direct economic benefit through electricity generation

Hydrogen fuel cells offer a compelling alternative to diesel generators for stationary power generation The principle behind this technology involves using hydrogen as fuel, which through an electrochemical reaction is converted into electricity. Unlike diesel generators, fuel cells operate quietly without any moving parts, which significantly reduces maintenance costs and enhances efficiency of conversion.

The hydrogen fuel cell based stationary power generation system is available in a variety of sizes ranging from 5kW to 50kW systems. Large system sizes are also possible but may not be easily available currently from the common suppliers. The stationary power generation system will primarily consist of the power generation unit and the hydrogen storage system. It is envisioned that the system may be used for 3 hours a day for 340 days in a year. Under this type of usage, it is envisioned to have a life of approximately 10 years during which some operation and maintenance (O&M) will be required annually. In addition to this, the hydrogen will need to be regularly replenished depending on the amount of storage and duration of daily utilization of the system. It is recommended to have a storage of sufficient size so as to require refueling only once in a few days. Otherwise, the hydrogen distribution may become a constraint in its smooth operation. Under these assumptions, the calculated cost per unit of electricity generated is 65/kWh.

These systems have been deployed heavily in Japan for domestic electricity generation applications. In Japan, there is a strategic focus on providing resilience to the grid in case of natural disasters and having fuelcell based power generation for homes fulfills this purpose.

Figure 4: Hydrogen power stationary power generation

Clean electricity (INR/kWh)

65

Operational benefits through space heating

Residual heat of fuel cells in the form of Combined Heat and Power (CHP) offers benefits which are specific to the fuel cell-based generation. Out of the total energy stored in hydrogen, around 50% is converted to electricity. Out of the remaining part approximately 45% of the energy of hydrogen fuel is available for heating purposes via exhaust of the fuel cell.The temperature of the air in the exhaust is 60-65oC which is ideal for space heating as well as water heating applications. In cold climates such as Leh, the heating load often accounts for 40% of the total electrical load. Hence, deployment of fuel cells (FCs) with combined heat and power (CHP) benefits has the potential of reducing the electricity consumption of the building also by up to 40%.

In Japan, this is effectively used for heating up of water which is then used either for space heating or other domestic chores. In the case of Ladakh which experiences extreme cold climatic conditions for 8 months of the year, the H2-FC stationary power generation systems would offer additional space heating benefits. During our discussions with the officials and personnel of the Indian Army as well as hotel owners, it was found that space heating is one of the major reasons for heaving electrical energy consumption. Many such systems which combine the electrical power generation and the heating capability of hydrogen fuel cell powered generators are installed in Japan and in many European countries. In Japan, such systems are popularly known as ENE-FARM and have seen around 4,00,000 installations so far.

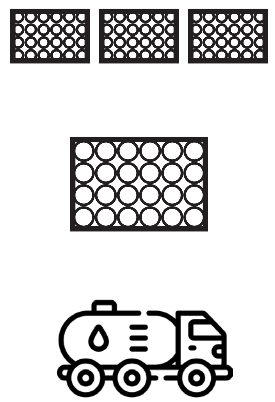
Hydrogen refueling infrastructure for power generation

Hydrogen will need to be transported to the individual locations where the stationary power generation units are located. These locations could be spread out throughout the city of Leh. For ensuring smooth and reliable delivery of hydrogen from the generation site to the place of consumption, a hydrogen delivery vehicle is proposed as shown above in Figure 5. This vehicle will have a large cascade of cylinders for hydrogen storage. The total estimated capacity of H2 storage on board would be 79.2 kg.

The primary objective of this vehicle would be to deliver hydrogen to locations where the stationary power generation systems are installed or for any other application which may come up in the future. This vehicle would also be used as a mobile refueling unit for helping any stranded H2-FCEV buses or trucks. The vehicle would also serve as an additional buffer storage in case the green hydrogen production exceeds the utilization and storage capabilities on any particular day.

These stationary power generation systems will include a suitably sized hydrogen storage unit. This unit will be regularly replenished with fuel by the proposed hydrogen refueling vehicle.

Figure 5. Hydrogen refueling vehicle and its specifications



Parameter	Value
Number of Manifolds per Truck	3
Number of Cylinders per Manifold	24
Maximum Operating Pressure	150 Bars
H2 Storage Capacity of Each Cylinder	1.1 Kg
Total H2 Storage Onboard	79.2 Kg

2c. Emissions reduction potential

Replacement of diesel-powered vehicles or diesel generators with hydrogen FCEVs or hydrogen FC powered stationary power generation has the potential to drastically reduce emissions of all four categories as summarized in Table 1. The four categories of emissions from diesel are as follows:

1. Carbon di-oxide emissions (CO2)

CO2 is a greenhouse gas which is linked to global warming. Using 1 litre of diesel results in about 2.6 kg of CO2 emissions.

2. NOx emissions

NOx emissions are caused due to the oxidation of nitrogen present in air in the internal combustion engine of a diesel generator. Usage of 1 litre of diesel results in about 4.8 g of NOx emissions and are directly related to respiratory problems in humans.

3. SOx emissions

Diesel as a fuel contains relatively high concentrations of sulphur. When the fuel is combusted inside the internal combustion engine, the sulphur reacts with the oxygen from air to form the SOx group of compounds. SOx emissions are related to acid rain. Using 1 litre of diesel results in 2.4 g of SOx emissions.

4. Particulate matter (PM) emissions

Particulate matter are very small unburnt particles of carbon and are commonly referred to as smoke. They are the only visible component of harmful emissions from diesel usage. Smaller particles are more harmful as they can stay in the atmosphere for longer and have more chances of entering into the respiratory tract. They are related to cancer, breathing problems and reduced lung capacity. Burning 1 L of diesel releases 1.92 mg of PM.

All the above four categories of emissions are completely avoided via the use of hydrogen-FC based power generation instead of diesel. The electrochemical oxidation of hydrogen inside a fuel cell is essentially smokeless and does not produce any CO2, NOx or SOx emissions.

A calculation of the total annual emissions from the various use cases is calculated and summarized in the table. For calculating the emissions, the average diesel fuel efficiency of the vehicles or generators is considered. Annual operation is assumed to be 340 days per year with a daily operation of 3 hours for the DG and 8 hours for the heavy vehicles.

"Just like Sikkim has made its mark as an organic state, efforts are being made to make Ladakh a carbon-neutral region"

- PM Narendra Modi, addressing the country on the occasion of 74th Independence Day.

Annual emissions savings

Figure 6: Estimated emissions savings by replacing diesel powered systems with hydrogen

Type of system	Number	Fuel type	Fuel consumption (Km/L or L/ kWh)	CO2 (tons)	NOx (Kg)	S0x (Kg)	PM2.5 (Kg)
Buses/ Trucks	6	Diesel	34 Km/L	550	980	490	0.39
Stationary Power Generators	600 kW	Diesel	0.4L/kWh	776	1410	705	0.6

03. Approach and work methodology for study

The work methodology for conducting the analysis and the system design and operational strategy are summarized in this section.

3a. System design and financial analysis

The proposed plan for green hydrogen production and localized utilization consists of four distinct parts which were evaluated independently. The work methodology is summarized in Figure 7. These are as follows:

Calculating solar rooftop potential

The solar rooftop potential depends on the number of houses, government buildings and commercial spaces in Leh. The cumulative rooftop area of these buildings is indicative of the total area available for installation of solar panels. The weather conditions in Leh and the solar irradiation has a major impact on the total electricity which can be generated from the installed solar panels.

Use cases of hydrogen in Leh

The total hydrogen to be generated from the project daily has been estimated on the basis of the total installed solar capacity and the electrolyzer size and efficiency. Considering local requirements and conditions, two use cases have been selected for detailed technical planning and financial analysis.

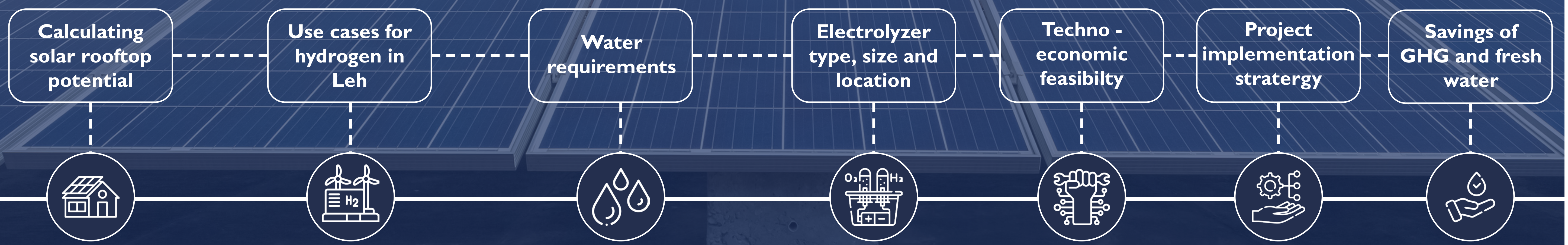
Water requirements

The water availability and water quality from the sewage treatment plant were evaluated for serving as a feedstock for green hydrogen production from the electrolyzer. The electrolyzer requires ultrapure water as a feedstock for ensuring optimum operating life. The quantity of water required by the electrolyzer of a range of sizes was considered and compared with the daily output of the sewage treatment plant. The usage of the STP water leads to fresh water savings, which were also calculated in this study.

Electrolyzer type, size and location

The electrolyzer type and size depends on the total energy and power availability from the solar installations and the water availability. Various sizes of electrolyzers were considered and an optimum size was determined for achieving a higher capacity utilization factor (CUF) leading to a lower LCOH (levelized cost of hydrogen).

Figure 7: Process flow for system design and financial analysis



Techno economic feasibility

The total quantity of daily hydrogen production is estimated. Several possible use cases of the hydrogen were considered. Based on the daily hydrogen production a prospective plan for the effective utilization of hydrogen is presented. The feasibility has been done in two parts, namely the cost of solar electricity generation (INR /kWh) and the levelized cost of hydrogen (INR/kg). For both calculations, the capital expenditure as well as the operating expenditure were considered. Based on the calculated LCOH, the operating cost (INR/km) of H2-FCEVs and the unit cost of electricity generation (INR/kWh) from the H2-stationary power generators was also calculated.

Savings of GHG and fresh water

The usage of hydrogen leads to the reduction of utilization of diesel resulting in substantial emissions savings across all categories (PM2.5, CO2, NOx and SOx). The resulting annual emissions savings are estimated.

3b. Operational implementation

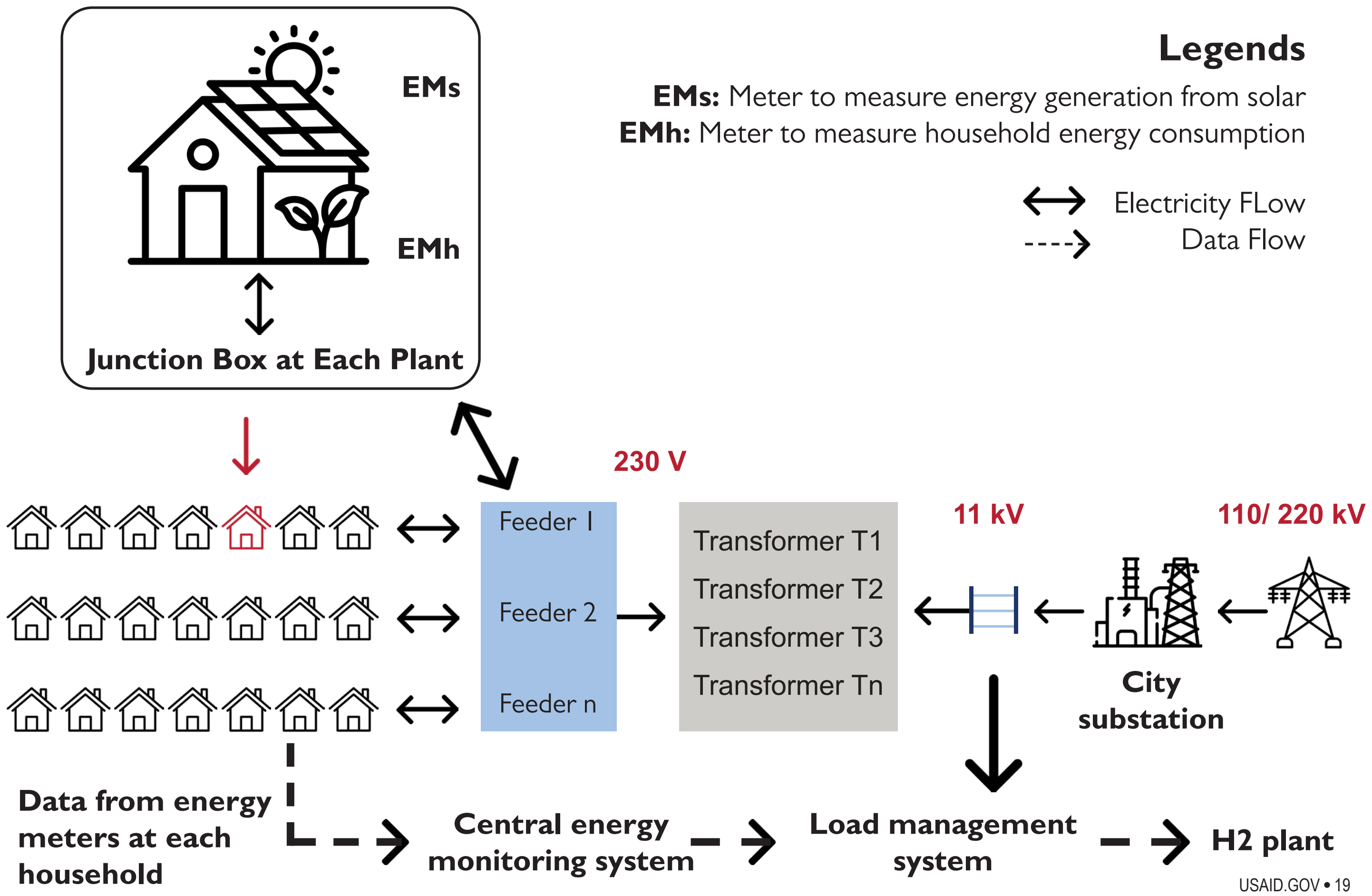
The proposed system design and operational strategy for the plant is summarized in Figure 9. The solar power generation will occur at the individual household, but the electricity will be drawn by the electrolyzer which is located close to the substation. An accurate measurement and datalogging of the real-time power generation by the distributed solar plant will be required to measure the total energy generation per day. The solar plant output will vary from morning to evening depending on the time-of-day. In some time slots of the day, the solar plant generation will be higher than the electrolyzer rated power (MW) and in other time slots, it will be lower. Due to this mismatch between the generation and utilization, balancing of the grid will be required and this will be managed by the grid operator. The electrolyzer plant will be operated for approximately 10 hours per day at its rated power.

In this project, the solar rooftops of houses and commercial spaces which are currently unused, will be utilized for the generation of renewable power for GH2 production and the treated water from the STP (sewage treatment plant) located at a distance of 5 km will be used as the feedstock. The individual size of the solar rooftop installation is likely to be 3 kW, which can fit on most of the rooftops in the city.

For this project, a total capacity of 7.2 MW is proposed to be installed which would consist of 2400 solar rooftop installations of 3 kW.

Figure 8: Hydrogen generation equipment at substation

Figure 9: Implementation plan

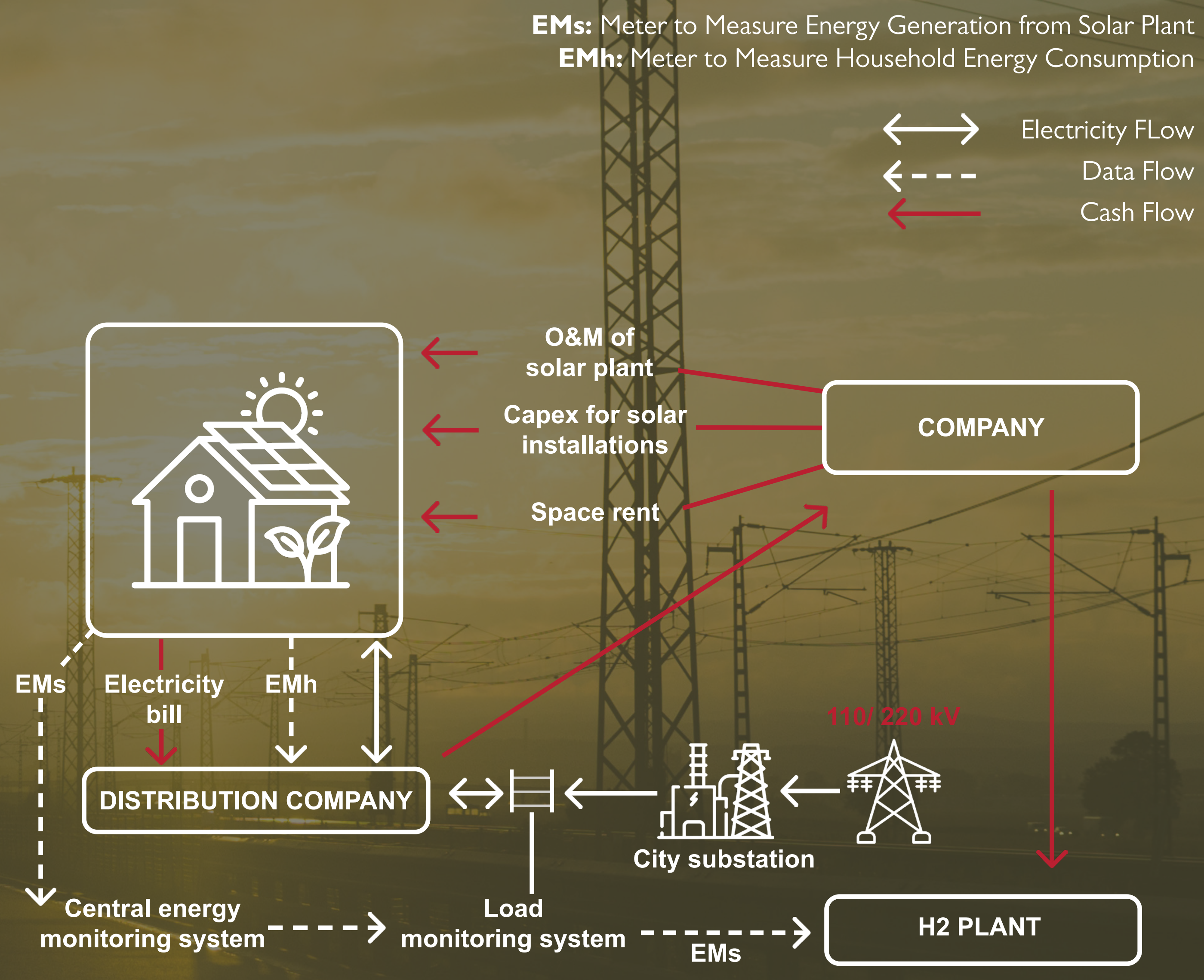


3c. Aggregating demand

A Special Purpose Vehicle (or company) will need to be set up which will be responsible for the installation, commissioning and O&M of the solar rooftop systems. The same company will also be responsible for scouting potential homeowners and business owners who are amenable to setting up solar panels on their rooftops in exchange for receiving a fixed monthly rent. It will be important to measure the total energy generated from the collection of individual solar installations for accounting purposes. The electrolyzer plant for green hydrogen production will be drawing an average of 20 MWh of electricity per day from the substation. However, the total electricity generation from the solar installations will be far in excess of 20 MWh and the remaining excess is to be sold to the electricity grid at Average Power Purchase Cost-APPC (INR/kWh).

The house or commercial building on who's rooftop the solar panel has been installed will continue to pay their monthly electricity bill as per their consumption. The installation of the solar panels on their rooftop will have no bearing on their consumption and their meter will operate completely independently of the solar power generation. The homeowner will receive a fixed monthly rent for providing their rooftop irrespective of the actual power generation happening from the solar rooftop system.

Figure 10: Generation of hydrogen and selling solar energy to the grid by aggregating demand



04. Estimation of solar rooftop potential

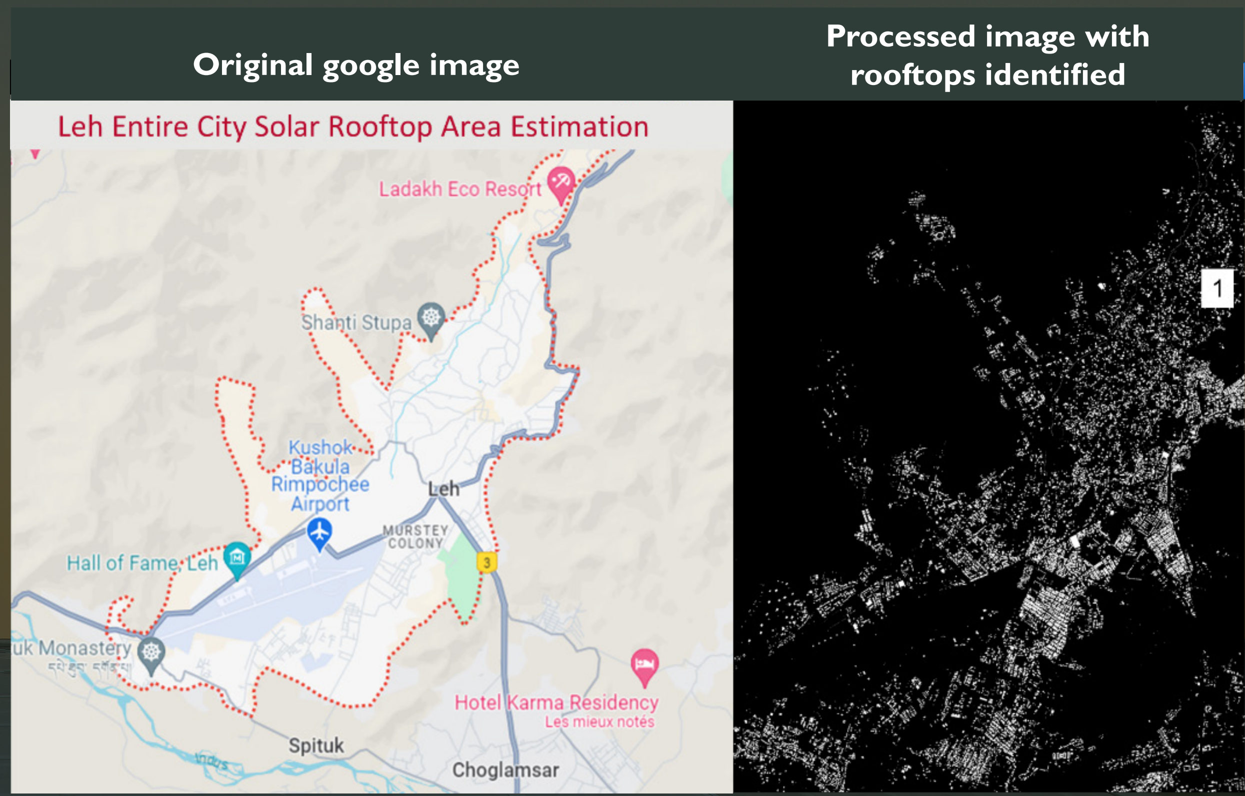
Rooftop area estimation is a critical aspect of this project as it allows us to estimate the total city-wide potential for solar installation. A particularly challenging aspect of this work is to calculate the rooftop area of individual houses as there is no regular pattern or standardized sizing of the houses. Previously, home to home surveillance type approaches have been used for such estimations. However, there are several challenges with this approach; the primary one being that it is highly resource intensive and time taking. Despite best efforts the sample size of the number of houses surveyed would still be small as compared to the number of houses in the region. This leads to large scale errors which can either overestimate or underestimate the solar potential.

To avoid these errors, in the current feasibility study, an advanced image processing approach using Google maps data has been employed. For this purpose, a specialized image processing algorithm and tool was developed which was optimized for solar rooftop estimation. The algorithm identifies the rooftop area from the map images and then by counting the number of houses as well as the rooftop area of individual houses.

Rooftop potential of the entire city is estimated to be 11.2 MW. Total recommended capacity installation for the current project is 7.2 MW. The buildings are of various sizes ranging from 50 m2 to > 1500 m2. A histogram of building sizes reveals that a large number of buildings lie in the range of 50-300 m2. The number of buildings of size greater than 500 m2 is much lesser, although these individual buildings may be able to accommodate larger individual solar installations.

The buildings are classified according to the solar installation which they can accommodate, and based on this, the final estimation has been made. Total rooftop potential has been estimated considering the people willingness, usable rooftop area and structural integrity of buildings.

Figure 11: Use of image processing for solar rooftop potential

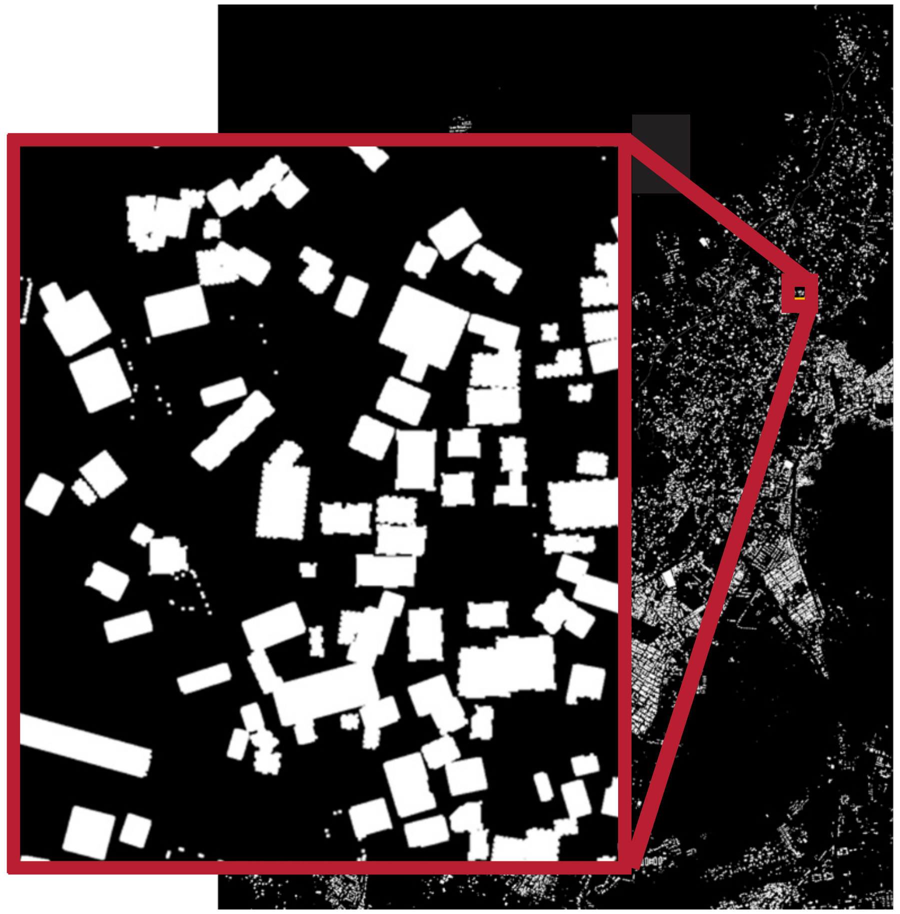


4a. Methodology for solar rooftop area estimation

Using image processing, an algorithm was run on the entire city (10 hours of processing time). The area was divided into 1500 grids and corresponding map images were downloaded from Google maps. All images were collated into a single large image (> 30 MB). The map of a larger area does not capture details like buildings. When zoomed-in, buildings become visible, but larger view is lost. To do analysis based on buildings aka rooftops, we need the map which captures building outlines in the map. There is no out-of-box service for such a big map. The mentioned problem has a prerequisite to create a bigger map that adequately represents buildings for processing. In this map, when converted to image, we can apply different image analysis techniques to achieve what we need.

To solve this prerequisite, we needed to develop a program that takes corner coordinates of a bigger area (say city) and creates the bigger map. Such a program takes the coordinates and tries to zoom in each section of the map. It stores that zoomed area as an individual image. By using this method the program converts small zoomed in areas into images. Those images are stitched together appropriately to create a big map image. This image shows buildings in a particular colour. Now once we have the bigger image, we need to find out how many buildings are there in that big image of a map. We also need to find out the approximate area of each building (as it is a satellite image, we have to consider an approximation here). Then the percentage of total building area with respect to total area of the map was calculated. As we see the maps carefully, the residential and commercial buildings are marked with a particular colour. Therefore, we can use colour analysis on the image to achieve our goal. With colour analysis of each building colour, we can determine the number of such coloured ed areas. The image size (width, height) and area size in square meter is known. From that we can calculate every coloured ed area in square meters. Similarly, for every coloured ed area, we know the position in the image and the resolution of the image. This way, we can translate it into longitude and latitude of every coloured ed area. If the buildings are nearby, it is hard to distinguish and so will be considered a single building. Depth is also lost in satellite imagery, so we have to do approximations there too. Thus, with coloured analysis, we can get the number of buildings, their approximate area and location (longitude/latitude) for a given area.

Figure 12: Processed image with rooftops identified



The downloaded images of the city map were collated into a single hyper-enlarged image for further image processing analysis. The buildings area were initially marked with a white colour and all non-building areas were marked with black colour. The non-building areas include roads, trees, open areas, water bodies and so on. The black and white image shown below emerged as a consequence of this colour coding. This image represents every house, commercial space, government building and any other dwelling in the city of Leh in a single image. After this step, the image processing algorithm was again employed on the B&W image to identify the size of each white closed area. From this exercise, an excel file was created which has the exact area of each building in the city along with the approximate location (latitude and longitude). The excel document containing the entire list has also been provided along with this study.

4b. Solar power generation potential

The normalized production of solar energy per kW of installed panels per day is shown in Figure 13. The solar generation potential in Leh is relatively high (4.89 kWh per kW of installed capacity per day) as compared to most parts of India. This is in part due to the clear weather conditions (low rainfall) and also due to the low temperature conditions which lead to higher solar panel efficiency. Seasonal variations are observed in the solar availability pattern (November-February are lower electricity generation months).

Day-to-day variation is relatively high even in the high power generation months. There are several days where the generation is much lower than the expected value due to weather related issues. Hence, an electrolyzer with a lower turndown ratio (Proton Exchange Membrane aka PEM electrolyzer) is suggested. Hourly energy generation also shows rapid variations on typical days and hence the electrolyzer technology chosen should be capable of responding to the variations.

Figure 13a: Daily solar irradiation at Leh

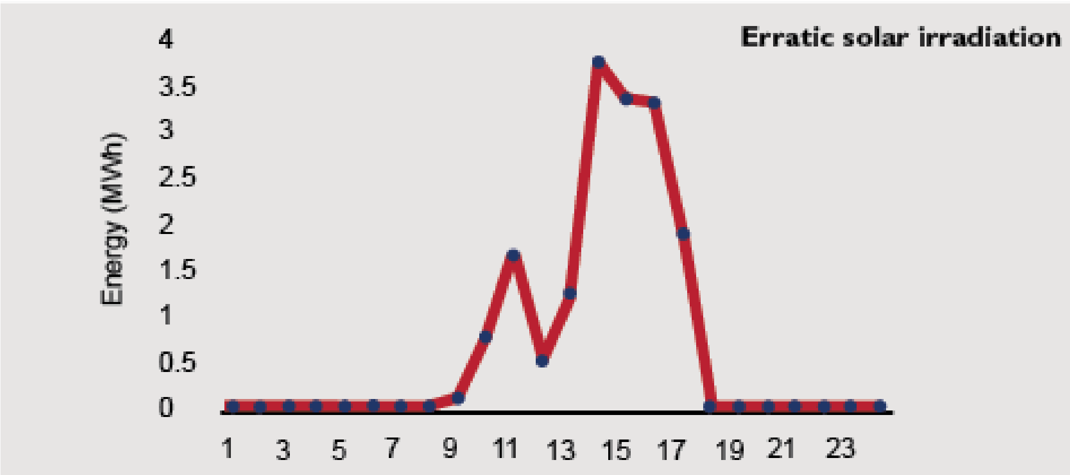
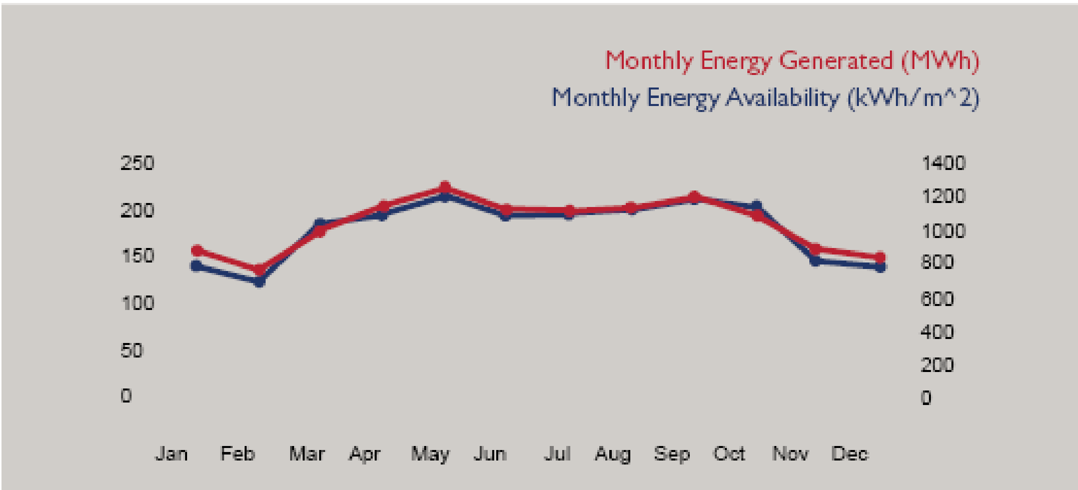


Figure 13b: Annual solar irradiation at Leh



4c. Matching electrolyzer energy requirements with solar irradiance

Although the general weather pattern in Leh is quite clear and the atmosphere has less dust and pollution content, the annual data reveals that there are several days with erratic solar irradiance.

There is significant day-to-day variation in solar irradiance throughout the year. This is true even for the month of May where the solar irradiance is relatively high as shown in Figure 13. This will have a direct impact on the daily generation of the green hydrogen and hence a reasonable amount of hydrogen storage is recommended. As per the proposed sizing, 330 kg of hydrogen storage has been suggested which is equivalent to the average daily green hydrogen production. During some days such as from the 9th to 13th May or between 26th to 28th May, there appear to be longer periods of lower daily energy generation.

However, the requirement of the electrolyzer of 20 MWh would still be generated on all days except the one day of the month. This much variability could be tolerated by the system easily. As per the analyzed data for the entire year shown in Figure 13, it can be seen that there are significant variations in the monthly power generation throughout the year. Monthly solar energy availability and generation profiles closely follow each other. Nov-Feb shows lower energy generation primarily because of lower solar irradiation. From March to Oct: Month of May shows the highest generation, while other months are close to each other. However, in all months the monthly power generation exceeds 600 MWh. This indicates that the daily energy generation would be higher than 20 MWh, which is the daily requirement of the electrolyzer.

05. Estimation of electrolyzer sizing and technology selection

A lower electrolyzer size of 2 MW is recommended for the current project. This size is much lower than the recommended solar capacity of 7.2 MW. This size difference will allow the electrolyzer to be operated at a relatively high CUF. The estimated average daily energy generation is 35.6 MWh. Out of this 20 MWh may be used by the electrolyzer and the rest may be fed into the grid. It is recommended that the electrolyzer be used for 10 hours per day (as per the solar availability) at the rated capacity of the electrolyzer. This will lead to a daily hydrogen generation of 330 kg. A lower turn down ratio and adaptability to high up/down ramp rates will be beneficial for the load balancing process. To minimize the water consumption and due to the small electrolyzer size, it is recommended that air cooling be used for the electrolyzers. Hydrogen storage facility may be required to balance out the generation and the usage (1 day of storage)

5a. Electrolyzer technology selection

Table 2 summarizes some of the key technical parameters for comparing the three existing electrolyzer technologies. The exact technical specifications differ slightly depending on the supplier of the system and averaged values have been presented below to bring out the broader differences between the technologies.

Figure 14: Comparison of key technical performance of electrolyzers

Parameter	PEM	ALK	SOEC
Turndown ratio (%)	10	15 – 30	25 - 30
Energy requirement (kWh/kg)	49 - 55	55 – 60	37 – 46
System sizes (MW)	Upto 20 MW	Upto 10 MW	Upto 5 MW
Startup time (min)	30 sec warm / < 5 min cold	5 min warm up / 30 min	> 2 hours
Shutdown time (min)	-	-	-
Output pressure (bars)	30 - 40	Upto 200	-
Stack lifetime (hours, years)	80000 h, 10 years	15-20 years	> 5 years
System lifetime (years)	15-20	20-25	-
Operating temperature (oC)	60 - 80	50 – 80	700
Ramp up / Down rate	High	Medium	Low

Few key observations from the above comparison table are summarized below:

- PEM and ALK (Alkaline) systems have a low stack operating temperature. Due to this, startup and shutdown times are much lower as compared to solid oxide electrolyzer cell (SOEC) systems. The SOEC stack operates at a very high temperature (< 650 C) resulting in very high startup and shutdown times. Frequent startup and shutdown of the system are not recommended unless necessary for repairing purposes as it severely shortens the life of the stack.

- ALK electrolyzer technology has been commercially in operation since the 1960s. The technology is very mature and has been proven to exhibit decades of operation in the field. PEM bases electrolyzers have been commissioned and operated successfully in various locations for 5-10 years.

- Electrolyzer output can be ramped down to lower than the rated power level during times of lower power availability. SOEC and ALK systems can be ramped down to 30% of the rated capacity, whereas PEM systems can be lowered to 10%.

- The energy requirement (kWh/kg) is a measure of the efficiency of the system in terms of converting the electrical energy to chemical energy (stored in Hydrogen). A higher efficiency translates to a lower kWh/kg, which is better for lowering the electricity consumption.

- The efficiency of systems exhibits the following trend: SOEC >> PEM > ALK. This difference is mainly due to the difference in the electrolyte and interfacial resistances in the cells in the stack which are much lower in SOECs due to their high operating temperature. Hence the kWh/kg of SOECs is lower than PEM and ALK electrolyzers. The remaining balance of plant energy consumptions are quite similar irrespective of technology.

- The output pressure of the available hydrogen is 30 bars. This pressure can be increased to the required pressure for the storage tank via the use of an external compressor. (See output pressure differences). ALK systems can generate a much higher pressure at the output, but this is done through an external compressor of the rate capacity and output pressure.

- ALK and PEM electrolyzers are technologically mature and solutions of sufficient size (MW) are available from multiple manufacturers to suit the requirements of the current project. ALK systems have a much longer history of operation and systems of larger size have been deployed and operated successfully for decades. PEM systems are developed more recently and have fewer installations.

Technically, both the alkaline and PEM electrolyzer technologies are suitable for the current project.

5b. Water vs. Air cooling

Electrolyzer stacks operate at approximately 65-75% efficiency of conversion of electrical energy to hydrogen fuel. This means that 25-35% of the total supplied electrical power is converted to heat energy in the stack and this requires a substantial amount of cooling to maintain the proper stack operating temperature. There are two major options to be considered for the cooling; each having their own advantages and challenges as summarized in Table 3.

Figure 15: Comparison of key technical parameters of air cooling and water cooling options

Parameter	Air cooling	Water cooling
Electricity consumption	Higher (COP ~ 2.5 - 3)	Lower (COP ~ 5 - 7)
System sizes	Suitable for smaller plants (~2 -10 MW)	Suitable for low to very large capacity plants (Can be built up to 1000's of MW/ToR)
Life span	15 - 20 years	20 - 30 years
Water consumption	Low water consumption (15-20 L/Kg H2)	Higher water consumption (35-60 L/Kg H2)

COP = *Coefficient of Performance

The major differences lie along the following four categories:

Electricity consumption

The air-cooling system utilizes the air flow over a heat exchanger to extract heat from the electrolyte. Since the specific heat capacity of air is relatively low (compared to water), a very high air flow is required to achieve the required cooling effect. The high air flow is achieved via electricity powered fans leading to a high electricity consumption. In the water-cooled system, the evaporative cooling effect of water is used for extracting the heat and large air flow is not required leading to lower electricity consumption.

Water consumption

In air-cooling there is minimal use of water and hence its water consumption per kg of H2 generated is low. In water-cooling, the evaporative cooling effect inherently leads to large water losses. These losses need to be compensated for by drawing more water leading to substantially higher water consumption.

System size suitability

For smaller electrolyzer plants such as 2-10 MW, air-cooling is an available option as it is compact and easy to implement. For larger electrolyzer installations such as 10-50 MW, water cooling is also a suitable option, and it can lead to enormous energy and cost savings.

Life span

For smaller electrolyzer plants such as 2-10 The air-cooling system consists of more moving parts which require higher O&M and have a relatively lower life-span as compared to water cooling systems.

The proposed electrolyzer installation is small (2 MW), the electricity tariff is quite low and the water availability in the Leh region is less. In addition to this, the year-round temperatures in Leh are quite low and this is beneficial for air-cooling. Keeping in mind these requirements and constraints of the Leh GH2 project, air-cooling appears to be the preferred option. A cost-benefits analysis should be done after receiving quotations for both types of cooling systems and based on that analysis, the final choice can be made.

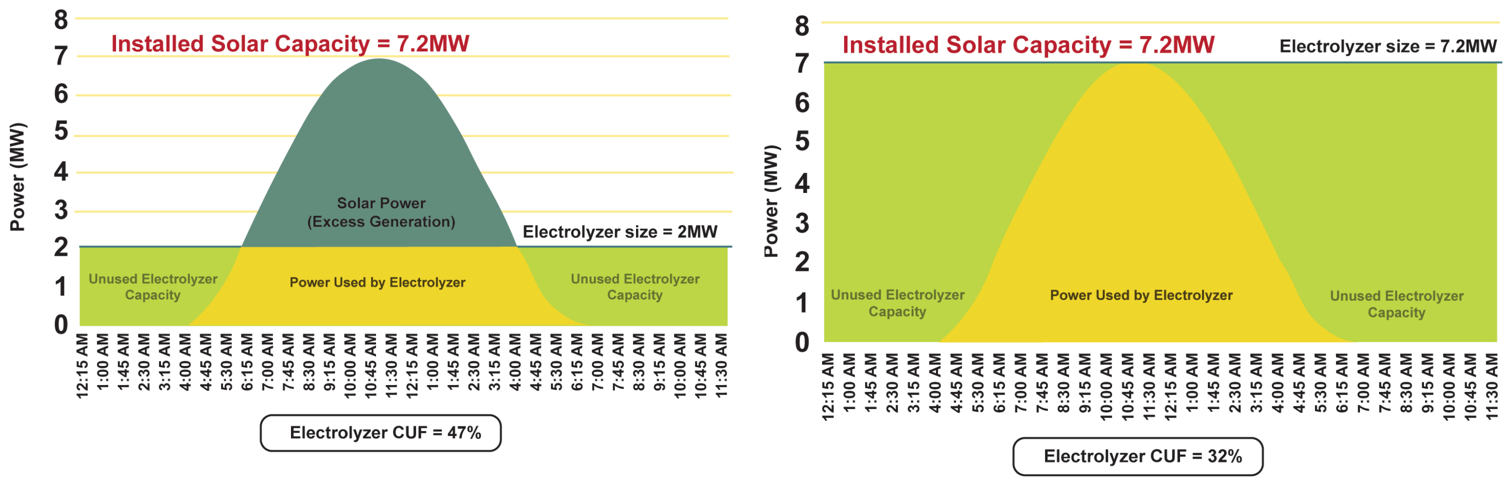
5c. Optimum electrolyzer sizing

In the current project, the recommended total solar installation size is 7.2 MW. Taking into account the solar radiation pattern in Leh, this plant would cumulatively generate approximately 7 MW, when the solar irradiation is the highest. If the electrolyzer is also sized to 7 MW, then it will be able to utilize almost all the power generated from the solar panels irrespective of the time of the day. However, the capacity utilization of the electrolyzer would be low as shown in the graph below. This is because the electrolyzer would operate at its rated power for only a very small part of the day when the radiation is the highest. It can be seen that in this case the capacity utilization of the electrolyzer is low (32%).

On the other hand, if the electrolyzer is sized much smaller than the solar installation, it will operate at its maximum rated power for a large fraction of the day (almost 10 hours). This would ensure much higher capacity utilization of the electrolyzer (47%) resulting in a lower LCOH.

In the second case, there would be a sizable fraction of the electricity generated from the solar installation which would not be utilized by the electrolyzer. This is because the generated power would be higher (> 2 MW) than the maximum rated power of the electrolyzer (2 MW). This excess power would be fed into the grid and would be utilized by the grid in serving their customers.

Figure 16: Effect of Electrolyzer sizing on the capacity utilization factor (CUF)



5d. Size of hydrogen storage

The requirement of hydrogen storage is estimated by analyzing the generation pattern over the entire day. The generation would be occurring primarily in the sunshine hours between 8 am to 5 pm. During the period, the electrolyzer would be functioning at its rated capacity for at least 7-8 hours. The consumption of hydrogen for the vehicle refueling would be happening between 7 am to 8 pm in the evening which is quite synchronized with the daily generation hours. It is expected that higher instances of refueling would occur either in the early hours of the day or in the late evening, before or after their daily vehicle usage.

The hydrogen refueling vehicle would be refueled multiple times in a day. This would be transported and supplied to the stationary power generation sites located throughout the city. The hydrogen refueling vehicle could be refueled in the middle hours of the day when the generation is at its peak but the dispensing for transportation purposes would be relatively lower.

Taking into account these considerations and the day-to-day variations in solar power availability, it is recommended to have 330kg of hydrogen storage. This is equivalent to the anticipated daily average hydrogen production.

06. Estimation of water requirement and technology selection

The electrolyzers require water as a feedstock for hydrogen production. Hence, the water requirements for the electrolyzer have been calculated for a variety of electrolyzer sizes (MW). Water requirement is quite low for the electrolyzers and the required quantities are easily transportable via water tankers. Capacity of individual tankers exceeds the daily requirement of the electrolyzer. Hence, proximity of the electrolyzer site to the STP plant site is not necessary. Limited water storage (2-3 days) can be set up on site at the Electrolyzer site. STP plants generally consist of Pre-, Primary and Secondary treatment facilities.

Tertiary treatment may have to be set up either at the STP plant location or at the Electrolyzer site. Ultra-purification will be done at the electrolyzer site. New Technology File System (NTFO) and Endpoint Detection and Response (EDR) technologies appear to have lower electrical energy consumption as compared to other alternatives. Thermal purification technology using the exhaust heat from electrolyzer could also be a suitable option. The STP plant

Figure 17: Requirement of pure water

Electrolyzer capacity (MW)	Daily H2 produced (Kg/day)	Total water required (Kg/Day)	Pure water required
2	330	6600	2970

Figure 18: Treatment of waste water for electrolyzer feedstock

The STP plant would have a Pre-treatment, primary and secondary treatment facility. A tertiary treatment system would need to be installed on the STP site to further treat the water. Ultra-purification system would be installed at the electrolyzer site for reaching the purity requirements of the electrolyzer feedstock water. NTFO, EDR and Advanced Thermal systems appear to be suitable for this process. NTFO and EDR systems have lower energy consumption as compared to Thermal. It is to be noted that the energy consumption of the chosen tertiary treatment system is miniscule as compared to the energy consumption of the electrolyzer (per kg of H2 produced). Hence, the primary factor for deciding the type of the water purification system would mainly depend on the capital costs and the output water quality. The total requirement of water per day is approximately 6600 kg or 6.6 tons.

Three technologies have been considered for the tertiary treatment of the water from the STP and have been compared on various critical parameters such as energy consumption, water recovery rate, capital costs, O&M costs and plant life as shown in Table 4. In the case of Leh, the water recovery rate is an important factor as there is water scarcity in the region. The normalized energy consumption is also crucial; a lower energy consumption would lead to lower operating costs and lower LCOH. Based on a comparison of all these parameters, both RO+EDI (Reverse osmosis and Electro-deionization) and NTFO technologies were found to be suitable. RO+EDI is an established technology for application with electrolyzers. However, NTFO promises to offer lower energy consumption, higher water recovery rate and lower O&M costs due to no requirement of regular membrane replacement. The downside of NTFO being that the capital expenses for setting up of this plant are relatively higher. In view of the potential benefits of NTFO and the future cost reduction potential, it is recommended to be used in the current project. However, it is also recommended that a more thorough cost benefits analysis should be done after receiving all quotations from the relevant suppliers. The capacity of all considered systems is 400 kg/h (output water).

Water purification technology selected due to lower energy consumption

NTFO

Figure 19: Comparison of water purification technologies

Parameter	RO + EDI	NTFO	Membrane + ion exchange
Energy consumption (KWh/m3)	9	2.7	4
Normalized energy consumption (kWh/kg of H2)	0.08	0.02	0.03
Water recovery rate	60%	>90%	90%-
Capital costs	0.4 Cr	0.95 Cr	0.6
O&M	Resin and Membrane Replacement after 3 Years	-	Resin and Membrane Replacement after 4 years
Plant life	>10	>10	>10

07. Site selection and consumer survey

7a. Site selection

The green hydrogen electrolyzer plant is recommended to be set up very close to the substation. This will allow the power to be easily drawn from the substation without any expensive upgrades to the distribution network. The peak power consumption by the electrolyzer is 2 MW and if the electrolyzers are set up far away from the substation, then the expenses on setting up the distribution line could be significant.

During the site visit, a substation near the Lungmar area was identified which has sufficient capacity to be able to support the power requirements of the green hydrogen production unit. In addition to the power capacity, there is also sufficient land availability in the immediate vicinity of the substation where the green hydrogen plant can be set up. This location is close to the road towards Khardungla and setting up of a refueling station can enable hydrogen-based transport on this route. There is also a river stream flowing in close vicinity of the substation. These are active during the periods of melting of snow and can provide an additional backup water supply in case there are any issues in receiving water supply from the STP as is planned for this project.

Figure 20: Substation identified near Lungmar area to setup green hydrogen unit

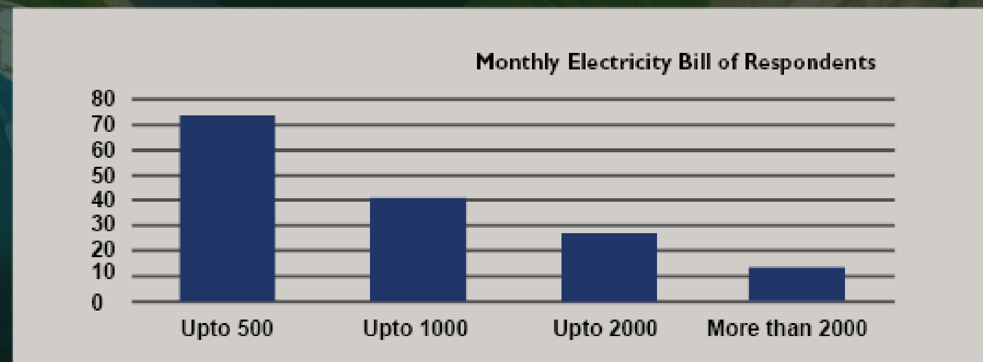
7b. Survey of local population: willingness for rooftop rental

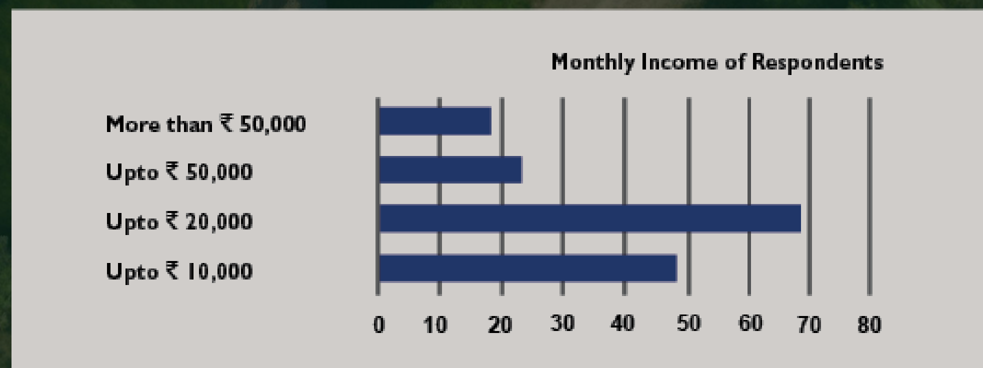
A comprehensive survey of local residents and homeowners was done to evaluate their willingness to allow installation of solar panels on their rooftops. A large majority of the respondents shared that their monthly electricity bill is either below INR 500 or INR 1000. A further 15% of the respondents mentioned that their bill is upto INR 2000. Very few respondents mentioned that their monthly electricity bill was greater than INR 2000.

The homeowners were also asked what their monthly family income was and this was also categorized into four categories as shown in Figure 21. A large majority of the respondents mentioned that their monthly income is upto INR 10,000 or upto INR 20,000. Around 15% of the respondents mentioned that their monthly income is upto INR 50,000 and 11% of the respondent said that their monthly income is above INR 50,000.

Based on the above two data sets it is recommended that the lower income homeowners be targeted for the solar rooftop installations. These would be the families that have their monthly income upto INR 20,000. They form a rather large fraction of the respondents and will also be keen to avail the type of incentives planned. Based on the monthly electricity bills, it is proposed that the monthly compensation for allowing installation of a 3 kW system on their rooftop should be INR 500.

Figure 21: Consumer survey results





08. Financial analysis

The levelized cost of dispensed green hydrogen (LCOH) has been calculated and presented in this section. This cost is used further to calculate the total cost of ownership for vehicles and stationary power generation.

8a. Cost of green hydrogen

The electricity tariff for distributed solar generation has been calculated taking important parameters in consideration as shown in Figure 22. This tariff is used as the input for estimating the LCOH. For the installation of rooftop solar plants, a subsidy is available from the central government and additional subsidy is available from the government of Leh.

Case 1: Realistic solar installation size

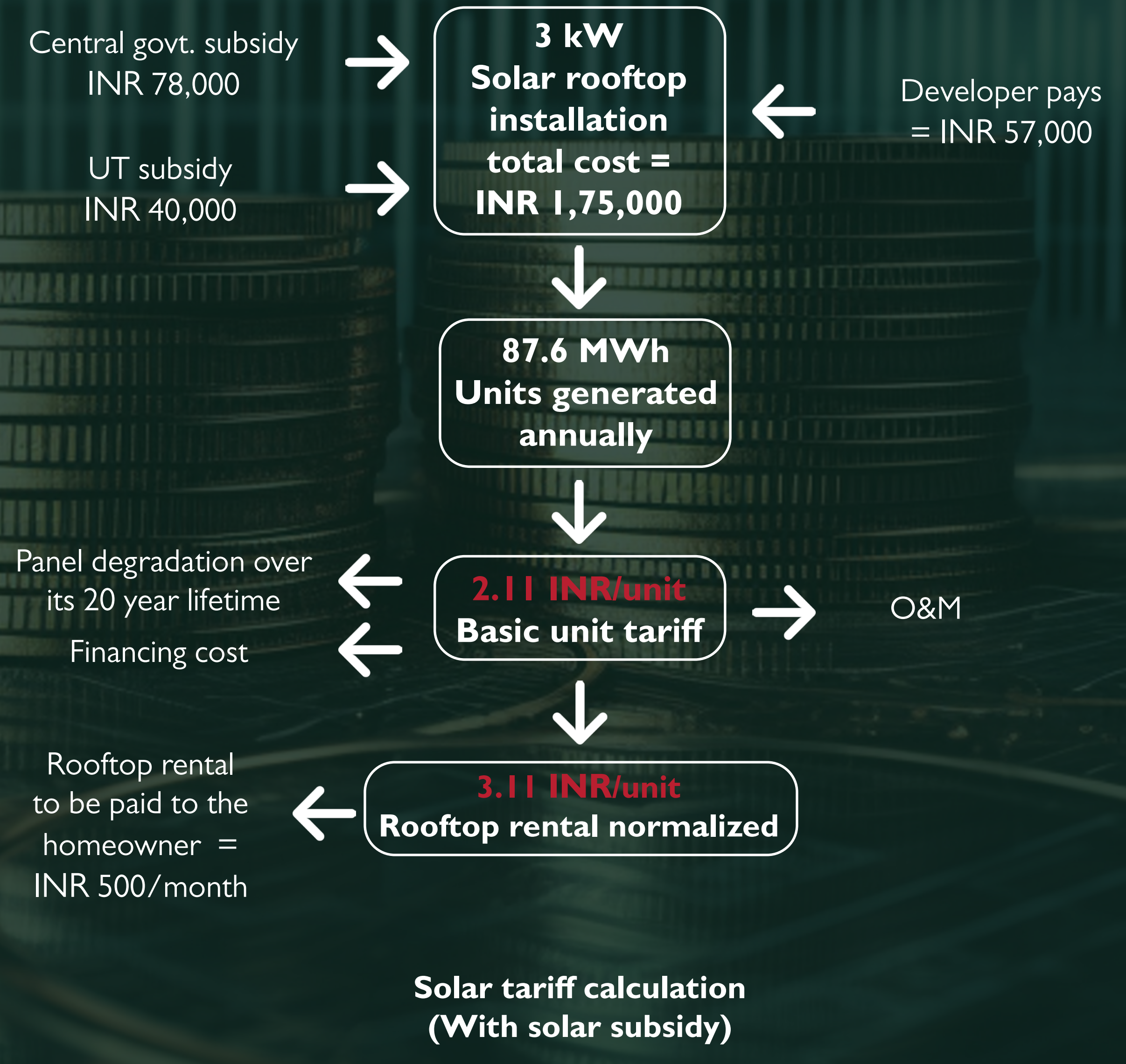
Realistic solar installation size if defined as the total number of installations of 3 kW required to reach the total installed capacity of 7.2 MW.

Cost of solar energy for production of hydrogen with rooftop subsidy

The standard installation size considered for this study is a 3kW solar rooftop installation. The cost of setting up and commissioning such a system from an empaneled supplier is INR 1,75,000 which includes the panels as well as the inverter and other BOP components. On this, the subsidy available from the central government is INR 78,000.

Additional subsidy of INR 40,000 is available from the government of Leh, which takes the total subsidy amount to INR 1,18,000. Hence, the effective capital cost of setting up one solar installation to the developer is INR 57,000 only. A 3kW system would be able to generate 87.6 MWh of electricity over its entire usable life of 20 years. This calculation of total electricity generation over its lifetime takes into account the year-on-year degradation and the solar irradiance pattern for the target location of Leh. This yields the tariff for electricity generation (2.11 INR/kWh). It is envisioned that homeowners would be paid a fixed monthly rental fee and this will cause an increase in the calculated tariff. Using this, a rental normalized tariff is calculated which is 3.11 INR/kWh which amounts to approximately INR 500/month.

Figure 22: Electricity tariff with rooftop subsidies, financing cost, O&M and rooftop rental payments to homeowners.

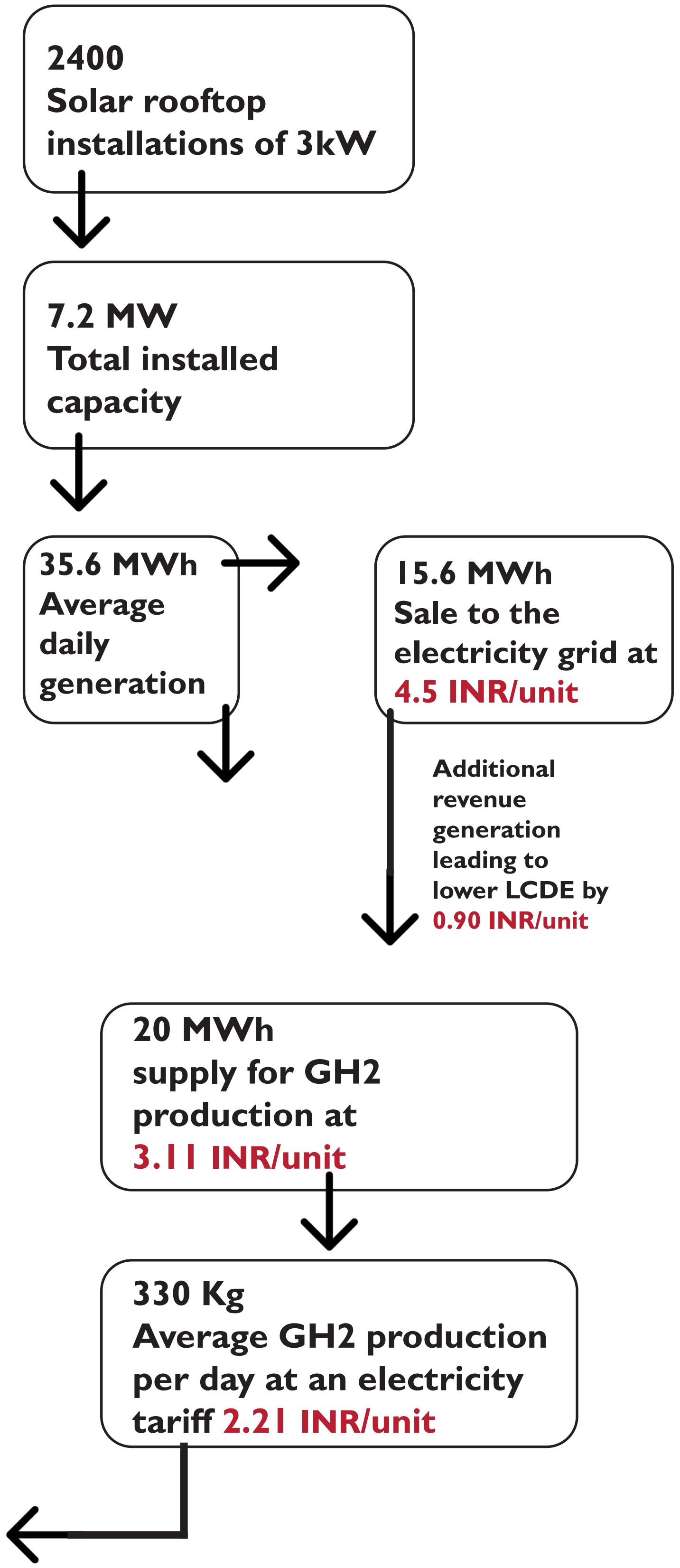


Cost of green hydrogen

A total of 2400 solar rooftop installations of 3 kW capacity will be required to meet the total installed capacity of 7.2 MW. The average daily generation of electricity will be 35.6 MWh. Out of this 20 MWh will be used for GH2 generation, whereas the remaining 15.6 MWh will be sold to the electricity grid at 4.5 INR/unit. This sale will generate an additional revenue, lowering the per effective electricity tariff will be lowered to 2.21 INR/unit. This final value of 2.21 INR/unit is used in all further calculations for the LCOH.

Cost of green hydrogen INR/Kg (Includes refuelling cost)

578



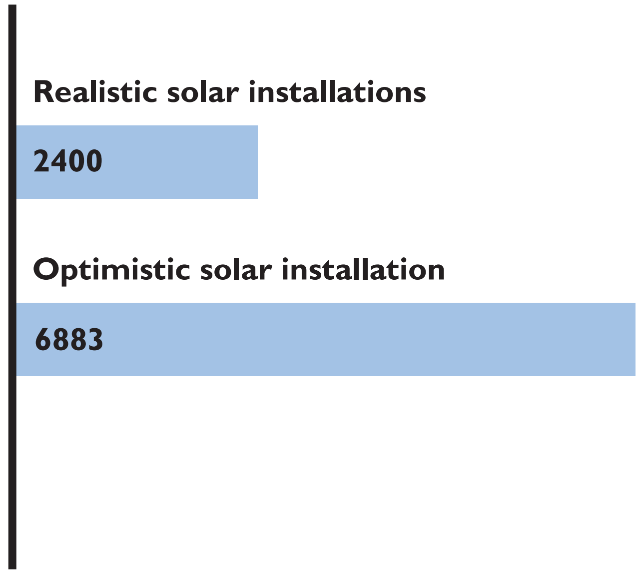
Case 2: Optimistic solar installation size

Optimistic solar installation size is defined as a very optimistic scenario of installation of 4300 solar rooftop plants (3kW) in addition to the 2400 plants mentioned in Case-1A. In this case the annual VGF requirement would be obliterated. There are a total of 12297 consumers connected in Leh town. Out of the total connections 6833 consumers are domestic in nature. Hence, such a target is highly optimistic. An attempt can be made to acquire maximum rooftops in one year and subsidies may be allocated according to the actual rooftop solar plants installed.
INR 440/ kg is the price of hydrogen in this case.

Case 3: Without solar rooftop subsidy

A calculation of the electricity tariff and the LCOH is repeated without incorporating the solar rooftop subsidy. This calculation is done to quantify and to clearly highlight the importance of the subsidy for the overall feasibility of the project. In the absence of the solar subsidy, the contribution of the capital expenses to the overall tariff increases significantly. Other contributing factors retain similar values.
Due to this the electricity tariff becomes 5.22 INR/kWh and the calculated LCOH becomes 719 INR/kg.

Figure 23: No. of residential installations



8b. Total project capital cost

The overall project will consist of many sub-systems such as the electrolyzer, water purification unit, hydrogen storage system, hydrogen dispensing unit, solar installations, H2-FCEV vehicles and stationary power generation systems. In the interest of the reader, a breakdown of the capital expenses has been shown in Figure 25. Broadly the three main contributors to the total capital expenses are the solar installation, the electrolyzer, the H2-FCEVs and the H2-Power generation systems. The hydrogen storage unit and the hydrogen dispensing unit are relatively lower cost contributors to the overall project cost. Figure 24 shows the individual contribution of the various factors to the final electricity tariff calculation. All the expenses such as capital expenses including financing costs, O&M costs and rooftop rental payment lead to a higher electricity tariff. On the other hand, the revenue generated from the sale of electricity to the grid leads to a reduction in the electricity tariff. The summation of all these contributing factors leads us to the final electricity tariff of 2.21 INR/kWh and the calculated LCOH comes to 578 INR/kg.

Figure 24: Contributing factors to final electricity tariff

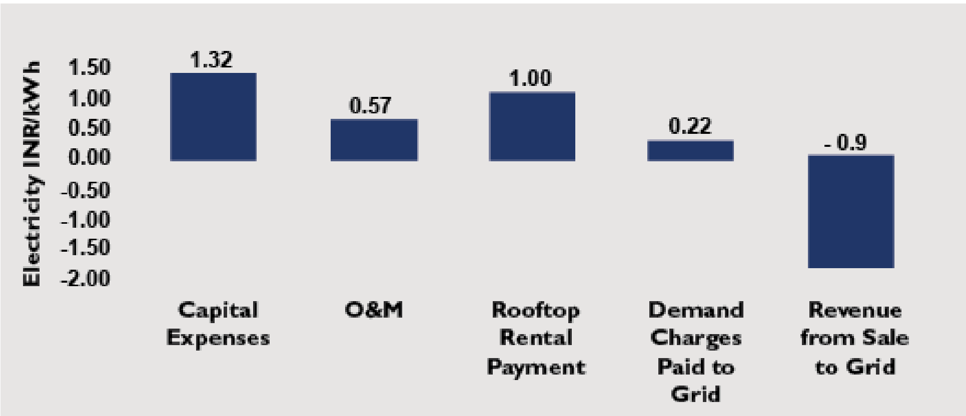
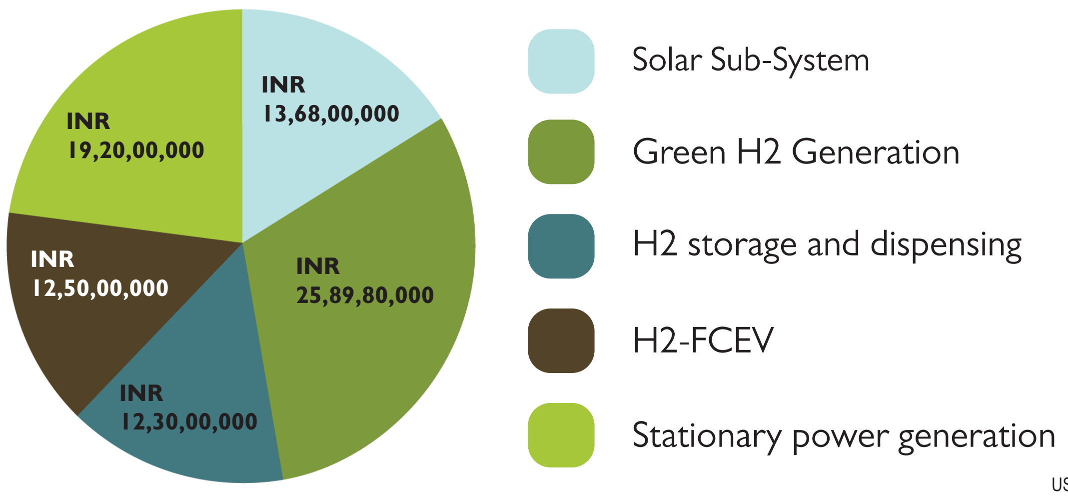


Figure 25: Contributing factors to captial expense



8c. VGF requirement

The all-inclusive operating cost of the truck/ bus (H2-FCEVs) is 104 INR/km. The Indian Army which is keen to include these vehicles in its fleet is willing to pay 80 INR/km leading to a difference of 24 INR/km. The fleet will consist of six vehicles which would be driven for an average 400 km per day and for 340 days per year. To make the business case viable, an annual VGF of 1.95 crore INR would be required.

The all-inclusive unit cost of electricity generated from hydrogen powered generators is 65 INR/kWh. The customers such as hotel owners are willing to pay 45 INR/kWh, which is equivalent to their current costs from diesel powered generators. The difference is 20 INR/kWh. The total units to be generated from hydrogen powered generators per year is 612 MWh. To make the business case viable, an annual VGF 1.22 crore INR would be required.

To enable the successful adoption of the H2-FCEV and the stationary power generators, a total viability gap funding of INR 3.17 crore/ year may be considered. Alternatively, a one-time support of 42% (INR 13.2 Cr) is needed for the Hydrogen generation, storage and dispensation system, 40 % (INR 6.6 Cr) support is required for procurement of 6 FCEVs (Buses and Trucks) and a capex subsidy of 42% (INR 10.75 Cr) is required to make the Fuel cell backup system viable. This amounts to a total one-time capex subsidy of INR 30.6 Cr.

Figure 26: Viability gap funding requirment

Application	Option A: Annual VGF for 25y	Option B: One-time VGF
Six Hydrogen Trucks and Buses	1. 95Cr.	6.6
330 Kg Hydrogen Generation, Storage and Dispensation System	1.22Cr.	13.2
600 kW Fuel Cell Backup System	-	10.75
Total VGF	3.17 Cr.	30.6Cr.

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